

Big-Bang Nucleosynthesis in comparison with observed helium and deuterium abundances – possibility of a non-standard model

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Abstract

Comparing the latest observed abundances of ^4He and D, we make a χ^2 analysis to see whether it is possible to reconcile primordial nucleosynthesis using up-to-date nuclear data of NACRE II and the mean-life of neutrons. If we adopt the observational data of ^4He by Izotov et al. [1], we find that it is impossible to get reasonable concordance against the standard Big-Bang nucleosynthesis. However, including degenerate neutrinos, we have succeeded in obtaining consistent constraints between the neutrino degeneracy and the baryon-to-photon ratio from detailed comparison of calculated abundances with the observational data of ^4He and D: the baryon-to-photon ratio in units of 10^{-10} is found to be in the range $6.02 \lesssim \eta_{10} \lesssim 6.54$ for the specified parameters of neutrino degeneracy.

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I. INTRODUCTION

Big-bang nucleosynthesis (BBN) provides substantial clues for investigating physical conditions in the early universe. Standard BBN produces about 25 % of mass in a form of ${}^4\text{He}$, which has been considered to be in good agreement with its abundance observed in a variety of astronomical objects [2–5]. The produced amount of ${}^4\text{He}$ depends strongly on a fraction of neutrons at the onset of nucleosynthesis, but is not very sensitive to the baryon-to-photon η ($\eta = n_b/n_\gamma$; $\eta_{10} = 10^{10}\eta$). Hence the produced amount of ${}^4\text{He}$ is used to explore the expansion rate during BBN, which can be related to the effective number of neutrino flavours [6]. In addition to ${}^4\text{He}$, significant amounts of D, ${}^3\text{He}$ and ${}^7\text{Li}$ are also produced. Because of its strong dependence on η , the abundance of D is crucial in determining η and consequently the density parameter of baryons Ω_b .

In spite of apparent success in standard BBN, recent observed light elements considered to be primordial have been controversial. Large discrepancies for ${}^4\text{He}$ observations emerge between different observers and modelers of observations: Rather high values of ${}^4\text{He}$ have been reported for H II regions in blue compact galaxies [1, 7]. It is noted that primordial abundance of ${}^4\text{He}$ is deduced from extrapolation to the zero metallicity [8]. Deuterium abundance has been observed in absorption systems toward high redshift quasars [9]. It should be noted that the value in D has been believed to limit the present baryon density (e.g. Schramm & Turner [10]). A low value of ${}^7\text{Li}$ observed in Population II stars reported by Bonifacio et al. [11] is considered to be due to depletion and/or destruction during the lifetimes of stars from a high primordial value [12, 13].

Recently, the half-life of neutrons has been updated from the previous adopted value of 885.7 ± 0.8 s [14] which has been used commonly in BBN calculations consistent with the observed abundances of ${}^4\text{He}$ and D. However, the latest compilation by Beringer et al. derives the mean-life to be 880.1 ± 1.1 s [15], which may suggest inconsistency between BBN and observational values. This indicates further inconsistency against η deduced by [16, 17].

The apparent spread in the observed abundances of ${}^4\text{He}$ should give rise to an inconsistent range of η . Apart from observational uncertainties, we have no reliable theories beyond the standard theory of elementary particle physics. It is assumed in standard BBN that there are three flavours of massless neutrinos which are not degenerate. However it is suggested by Harvey and Kolb [18] that lepton asymmetry could be large even when baryon asymmetry

is small. The magnitude of the lepton asymmetry is of particular interest in cosmology and particle physics. Related to neutrino oscillations, investigations of BBN have been reprised with use of non-standard models (e.g. Ref. [19]). As presented by Wagoner et al. [20] and Beaudet & Goret [21], the abundances of light elements are modified by neutrino degeneracy (see previous investigations [22–25], see also review by Ref. [26]); it could be necessary and crucial to search consistent regions in η within a framework of BBN with degenerate neutrinos by comparing with the latest observation of abundances of He and D.

If neutrinos are degenerate, the excess density of neutrinos causes speedup in the expansion of the universe, leaving more neutrons and eventually leading to enhanced production of ^4He . On the other hand, degenerate electron-neutrinos shift β -equilibrium to less or more neutrons and hence change abundance production of ^4He . The latter effect is more significant than the former. In the present paper we investigate BBN with including degenerate neutrinos and using up-to-date nuclear data. Referring to several sets of combinations for recent observed abundances of ^4He and D, we derive consistent constraints between η and the degeneracy parameter.

In § II we summarize the current situation of observed abundances of light elements. Our results of BBN with updated nuclear data are presented in § III. Discussion is given in § IV.

II. OBSERVED ABUNDANCES OF ^4He , D, AND ^7Li

There exist very large spreads in some observed abundances of light elements due to different observational methods. Let us describe how we adopt the observed primordial abundances.

The primordial abundance of ^4He can be measured from observations of the helium and hydrogen emission lines from low metallicity blue compact dwarf galaxies. Izotov et al. reported the ^4He abundance from a subsample of 111 HII regions as follows [1]:

$$Y_p = 0.254 \pm 0.003. \quad (1)$$

It should be noted that primordial abundance of ^4He could be appreciated to the zero-metallicity in terms of an extrapolation by a model of chemical evolution of galaxies. An alternative low value on the average is reported by Aver et al. [8]:

$$Y_p = 0.2464 \pm 0.0097 \quad (2)$$

which has a very large spread in errors.

Deuterium is the most crucial element to determine η because of the strong and monotonic dependence on η . Its primordial abundance is determined from metal-poor absorption systems toward high redshift quasars. Cooke et al. have performed measurements at redshift $z = 3.06726$ toward QSO SDSS J1358+6522 [9]. Additionally, they have analysed all of the known deuterium absorption-line system that satisfy a set of strict criteria,

$$\text{D}/\text{H} = (2.53 \pm 0.04) \times 10^{-5}. \quad (3)$$

This value corresponds to the baryon density $\Omega_b h^2 = 0.02202 \pm 0.00046$ which is consistent with the results of Planck experiment [16, 17]. Here h is the Hubble constant in units of 100 km/s/Mpc.

We should note that the observed abundance of ${}^7\text{Li}$ in Population II stars is given by Sbordone et al. to be [27]:

$${}^7\text{Li}/\text{H} = (1.58 \pm 0.31) \times 10^{-10}, \quad (4)$$

which has been advocated to be rather low compared with BBN. While, considering significant depletion and/or destruction during the lifetimes of Population II stars, Korn et al. have derived a high primordial abundance [12]:

$${}^7\text{Li}/\text{H} = (2.75 - 4.17) \times 10^{-10}, \quad (5)$$

a value which is still too low to reconcile with the result of BBN. It is noted that Li can be produced together with Be and B through spallation of CNO nuclei by cosmic ray protons and α -particles. About 10 % of ${}^7\text{Li}$ could be due to cosmic ray processes leaving remainder as primordial [28, 29]. Among a variety of observational data, we here pick up only representatives of ${}^4\text{He}$ and D which we adopt in terms of symbols.

III. BIG-BANG NUCLEOSYNTHESIS

A. Standard Big-Bang Nucleosynthesis

Let us compare the calculated abundances in BBN with the observed ones. It is emphasized that standard BBN fails to find consistent range of η for the observed values given in

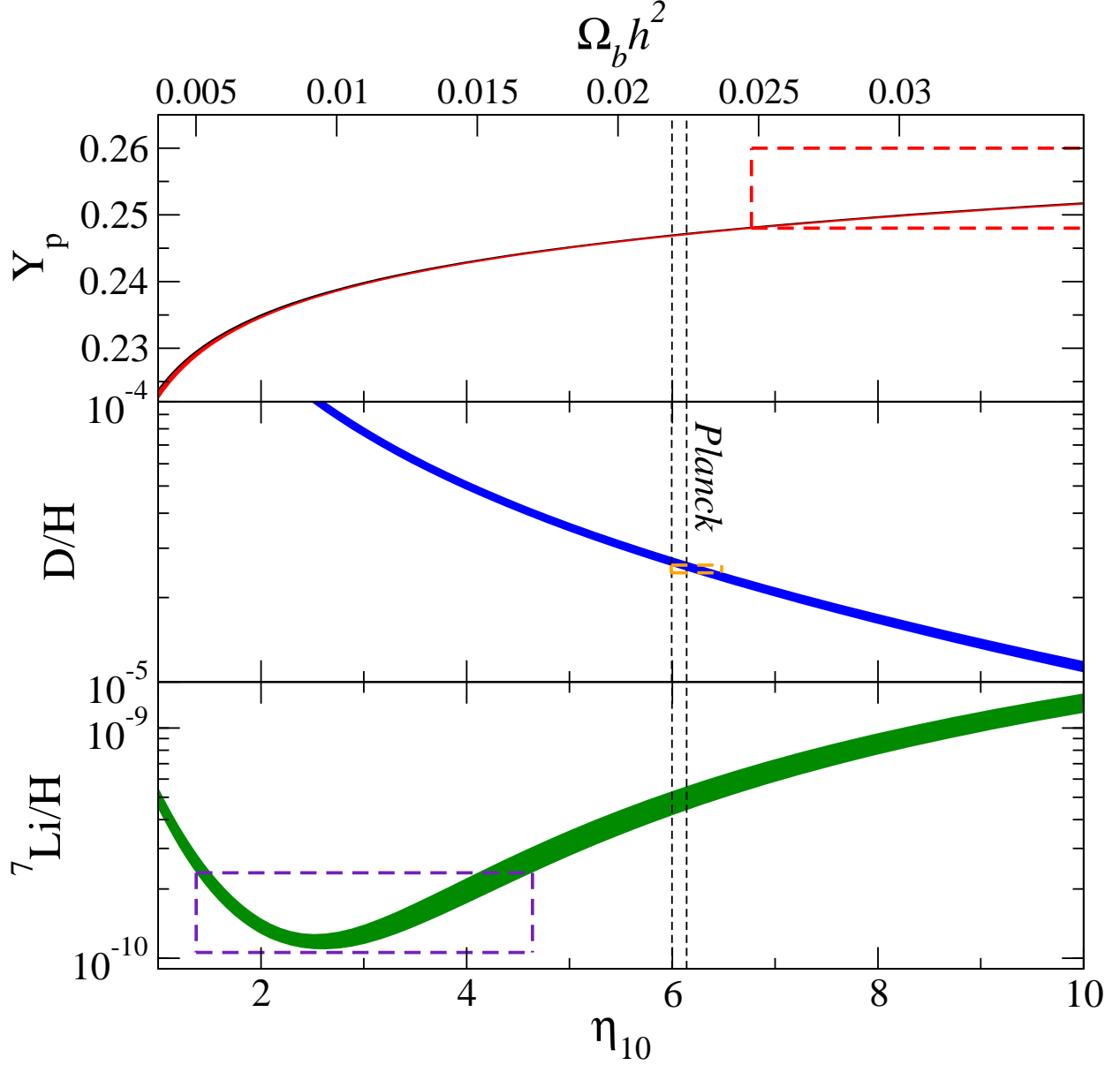


FIG. 1: Primordial abundances produced in a standard model as a function of η_{10} with use of the nuclear data of NACRE II and the mean-life of neutrons by Beringer et al.[15]. The vertical band indicates the result of Planck [17]. The boxes show the observational abundances of ${}^4\text{He}$ [1], D/H [9], and ${}^7\text{Li}/H$ [27] with 2σ uncertainties.

(1) and (3) as explained below. Nucleosynthesis is calculated with use of a network constructed by Hashimoto & Arai [32], where the reaction rates are taken from NACRE II [30] supplemented by Descouvemont et al.(DAA) [31], Caughlan & Fowler [33], and Ando et al. [34].

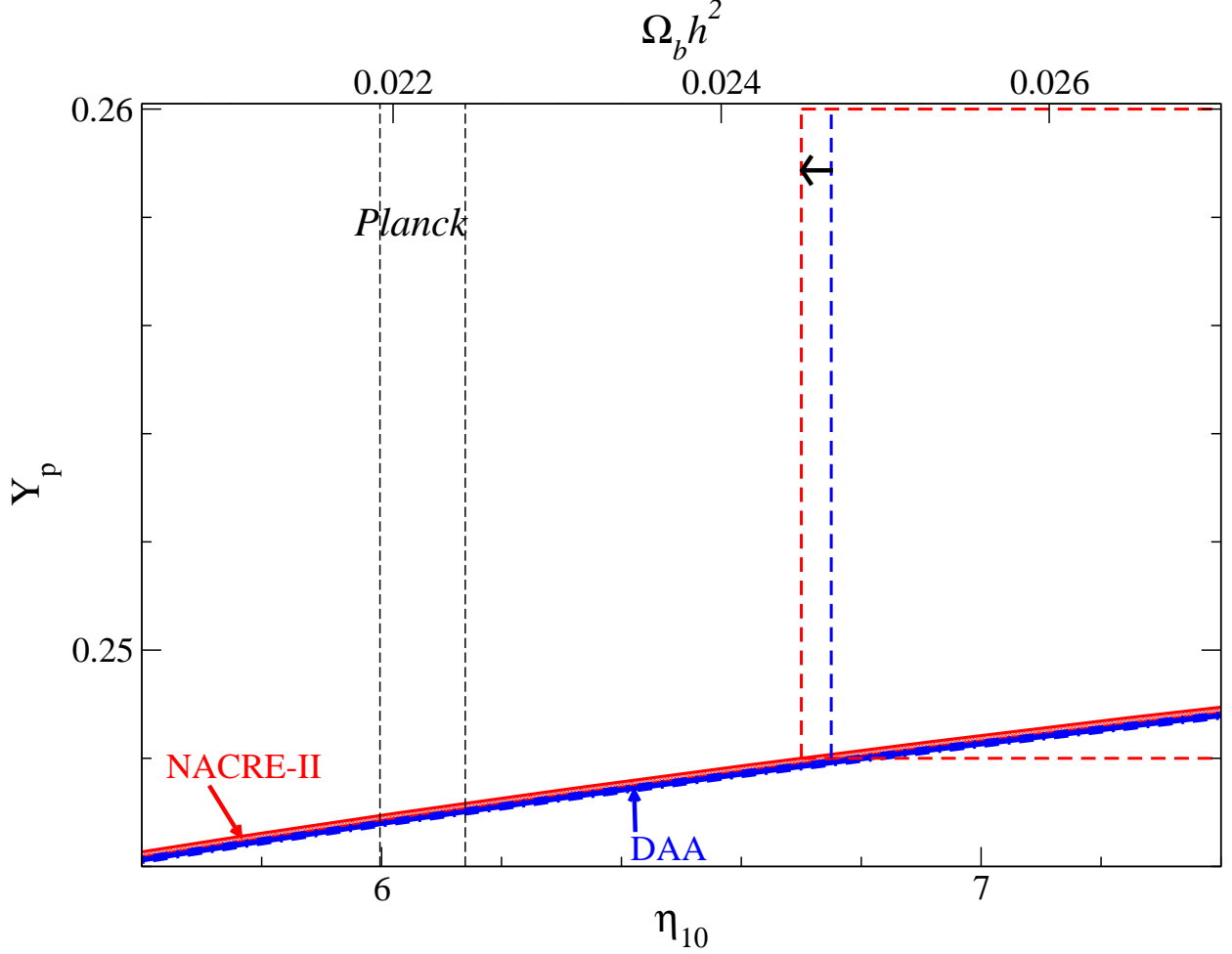


FIG. 2: Effects of reaction rates on the production of ${}^4\text{He}$. The red line is drawn using NACRE II [30] and the blue one is due to DAA [31]

The mean-life of neutrons is taken to be 880.1 s [15]. Now the mean-life becomes drastically short compared to the previous value of 885.7 s [14]. Using χ^2 -analysis for measured mean-lives, Beringer et al. [15] have obtained the up-dated (recommended) value to be $\tau_n = 880.1 \pm 1.1$ s within the 1σ level.

We set the number of neutrino species to be 3 for simplicity. We adopt the present CMB temperature of 2.725 K [35].

In Fig. 1, we compare observed abundances of ${}^4\text{He}$, D, and ${}^7\text{Li}$ with BBN, assuming 1σ errors for the nuclear reaction rates. We cannot find an overlapped region for the observational data between He by Izotov et al. [1] and D by Cooke et al. [9]. We also compare the baryon-to-photon ratio obtained from our calculations with the range $5.98 \leq \eta_{10} \leq 6.16$ derived from *Planck* observation. Contrary to the concordance with Planck result for D, the

abundances ^4He and ^7Li give no consistent range of η .

Figure 2 shows the uncertainties in the produced abundance of ^4He due to the alternative reaction rates of NACRE II and DAA. The difference $\delta\eta_{10} \sim 0.07$ between the two groups is very small and therefore does not resolve the inconsistency.

B. BBN with neutrino degeneracy

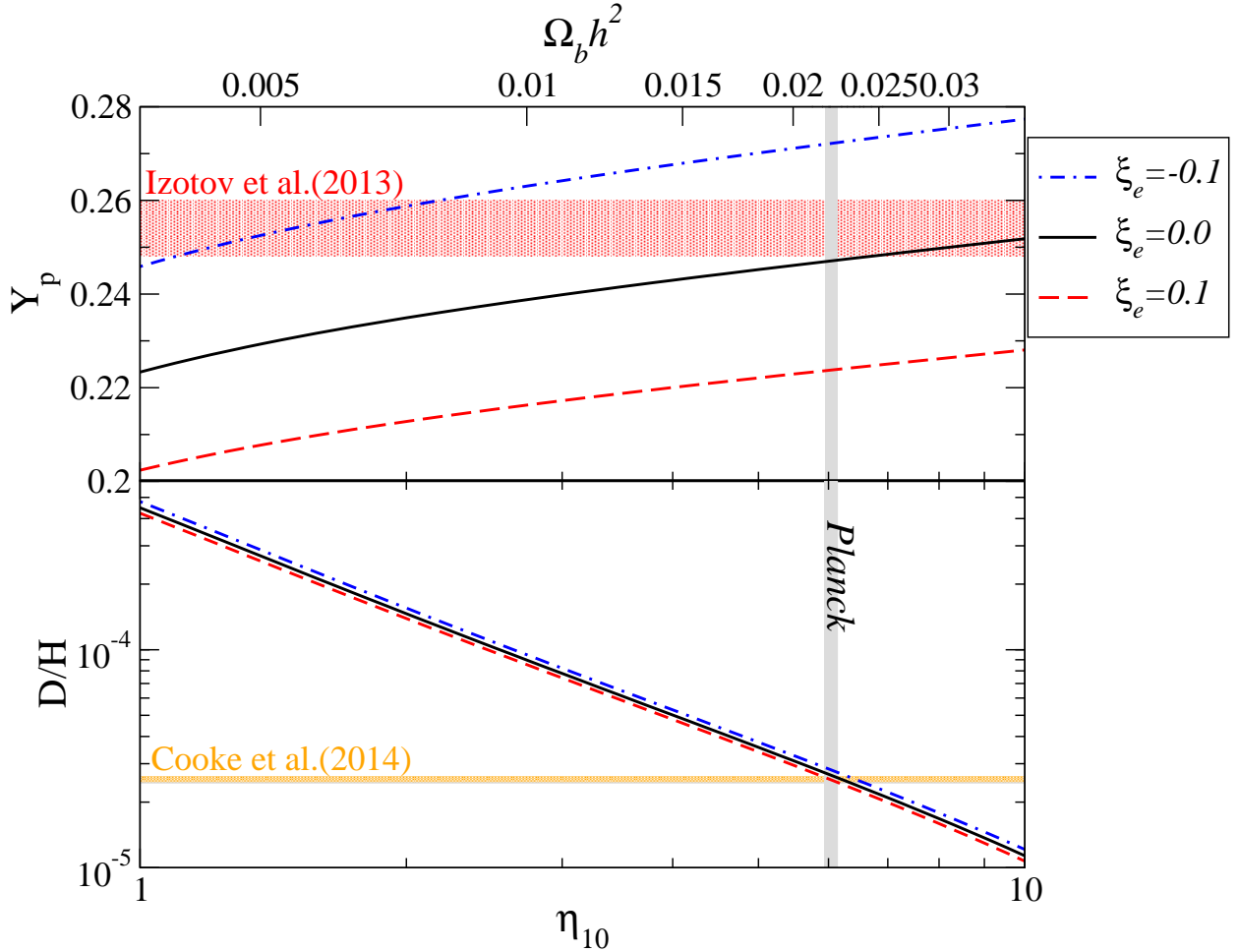


FIG. 3: Effects of neutrino degeneracy on the production of ^4He and D/H . The degeneracy parameters is taken to be $\xi_e = -0.1, 0$, and 0.1 from the top to bottom curve. The vertical band comes from the baryon density determined by *Planck*. The horizontal bands correspond to the observational abundances of ^4He and D/H with 2σ uncertainty.

Within the framework of general relativity, BBN can be, for example, extended to include neutrino degeneracy (e.g. Ref. [36]). Degeneracy of electron-neutrinos is described in terms

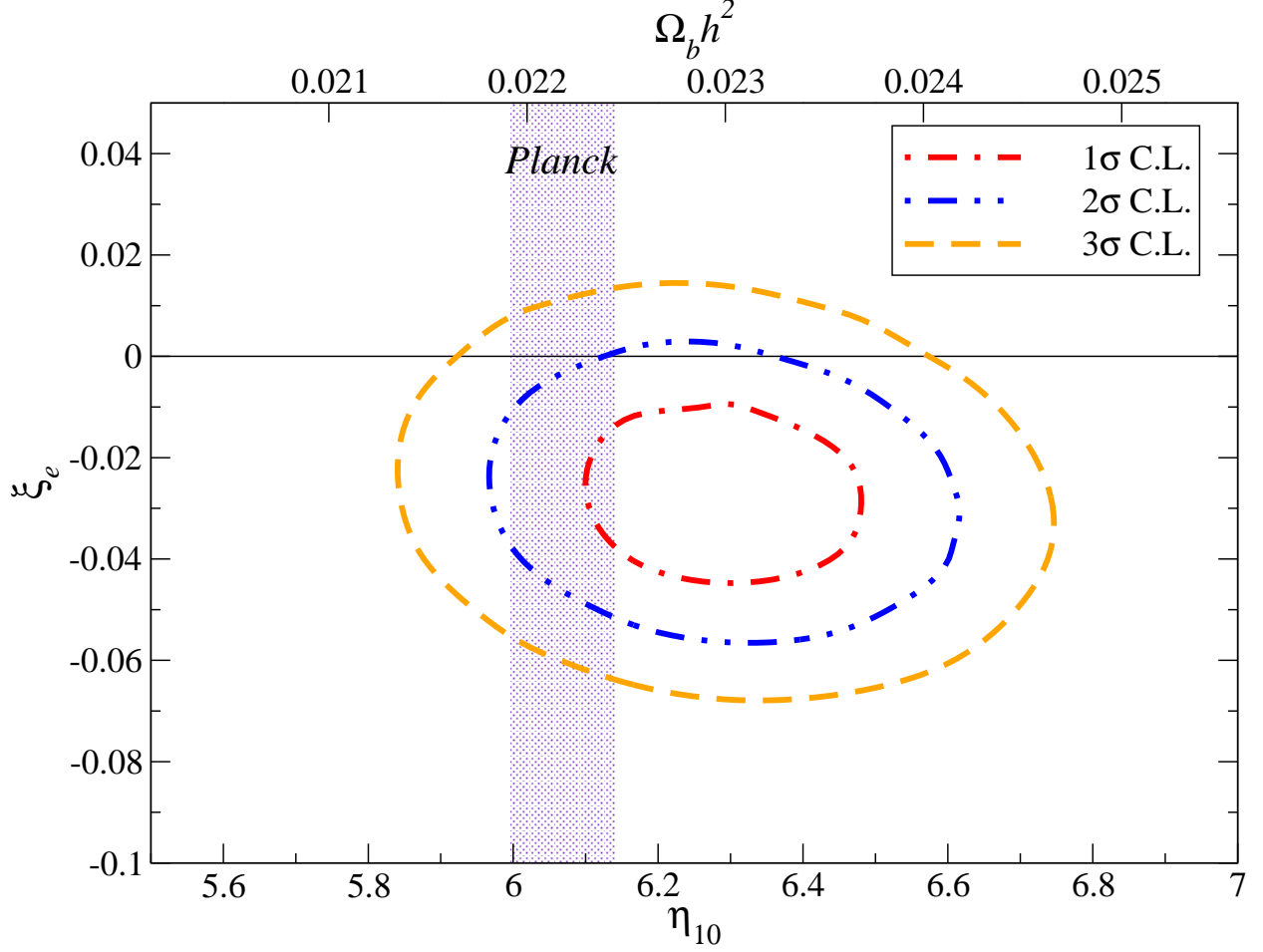


FIG. 4: Contours having 1σ , 2σ , and 3σ confidence levels from Y_p and D/H observations on the $\eta_{10} - \xi_e$ plane. The horizontal line corresponds to SBBN ($\xi_e = 0$). The vertical band shows the baryon density from *Planck*.

of a parameter

$$\xi_e = \mu_{\nu,e}/kT_\nu, \quad (6)$$

where $\mu_{\nu,e}$ is the chemical potential of electron neutrinos and T_ν is the temperature of neutrinos. To get abundance variations of both neutrons and protons against ξ_e , we take a usual method to incorporate the degeneracy into the Fermi-Dirac distribution of neutrinos [36]. In this study, we do not consider the degeneracy of τ - and μ -neutrinos.

In BBN calculations, we implemented the neutrino degeneracy as follows. Before the temperature drops to the difference Q/k in the rest mass energies between a neutron (n) and a proton (p), they are in thermal equilibrium through the weak interaction processes: $n + e^+ \rightleftharpoons p + \bar{\nu}_e$, $n + \nu_e \rightleftharpoons p + e^-$, and $n \rightleftharpoons p + e^+ + \bar{\nu}_e$. Below $T = 4$ MeV, we solve the

rate equations for n and p until T drops to 1 MeV including the individual weak interaction rates. After that, we begin to operate the nuclear reaction network with the weak interaction rates between n and p included. We should note that in the present parameter range shown later, effects of neutrino degeneracy on the expansion and/or cooling of the universe can be almost neglected, because the absolute values of neutrino degeneracy are rather small effects on energy density at most 10^{-3} %. (see Fig.4).

The produced amounts of D and ${}^7\text{Li}$ are almost the same compared to the case of the standard BBN, while ${}^4\text{He}$ becomes less abundant if $\xi_e > 0$, because β -equilibrium leads to lower neutron production. This is because, the abundance ratio of neutrons to protons (n/p) is proportional to $\exp[-\xi_e]$. This can be seen in Fig.3; while the abundance of ${}^4\text{He}$ is very sensitive to ξ_e , it is insensitive to η . On the other hand, although the abundance of D is almost uniquely determined from η , i.e., the nucleon density, it depends weakly on ξ_e .^t

When ξ_e increases, the produced amount of ${}^4\text{He}$ decreases. On the other hand, when ξ_e becomes negative, more neutrons survive to yield more ${}^4\text{He}$ as seen in Fig.3. It should be noted that the production of D is only weakly affected by ξ_e .

To find reasonable values of ξ_e and η_{10} which satisfy the consistency between BBN and observed ${}^4\text{He}$ and D, we calculate χ^2 as follows:

$$\chi^2(\eta, \xi_e) = \sum_i \frac{(Y_i^{th}(\eta, \xi_e) - Y_i^{obs})^2}{\sigma_{th,i}^2 + \sigma_{obs,i}^2}, \quad (7)$$

where Y_i and σ_i are the abundances and their uncertainties for elements i ($i = Y_p, \text{D}$), respectively. The value $\sigma_{th,i}$ is obtained from the Monte-Carlo calculations using 1σ errors associated with nuclear reaction rates. The observational values, Y_i^{obs} and their errors $\sigma_{obs,i}$, are taken from (1) and (3).

Figure 4 shows the contours having 1σ , 2σ , and 3σ confidence levels (C.L.) on the $\eta_{10} - \xi_e$ plane obtained (7).

In consequence, we get the following constraints for both η_{10} and ξ_e with the 1σ C.L.:

$$6.17 < \eta_{10} < 6.38 \quad -3.4 \times 10^{-2} < \xi_e < -1.8 \times 10^{-2}, \quad (8)$$

and with the 2σ C.L.:

$$6.02 < \eta_{10} < 6.54 \quad -4.6 \times 10^{-2} < \xi_e < -0.4 \times 10^{-2}. \quad (9)$$

It is noted that, except for neutron decay, two-body reactions are dominant during BBN. The weak reactions are only β -decay of ${}^3\text{H}$ with $\tau_{1/2} = 12.33$ y and e-capture of ${}^7\text{Be}$ with $\tau_{1/2} =$

53.29 d [47]. These half lives are modified by a small factor through neutrino degeneracy. However, the final abundance is not affected at all.

IV. DISCUSSION

While a large spread in errors of ^4He by Aver et al. [8] hinders us from constraining the amount of the produced ^4He abundance, a smaller range by Izotov et al. [1] permit us to constrain the ^4He production. Our results clarify the present controversial situation between standard BBN and observations; the effects of uncertain mechanism originated from a non-standard theory should reflect the ratio of n/p .

If we adopt the value in (9), we can obtain the following range for ν density parameter:

$$0.0220 \leq \Omega_b h^2 \leq 0.0239,$$

which is compatible with that from *Planck* measurements. We showed that the neutrino degeneracy may become one of solutions to solve the discrepancy concerning the present baryon density between BBN and CMB. Our results provide a narrower range of ξ_e compared with the previous study, e.g. Ref.[37]. BBN alone seems to give a strong constraint on parameters of a non-standard model such as the neutrino degeneracy.

The ^7Li abundance in the present calculation is still larger than the observational values (4) and (5). For the apparent discrepancies among the nuclear data and observations, we may need a non-standard model beyond Friedmann model: For example, the expansion rate in the universe could deviate significantly in a framework of a Brans-Dicke theory [38–41], or a scalar-tensor theory of gravity [42, 43].

If inhomogeneous BBN [44, 45] could occur in some regions in the universe, it may solve the problem concerning ^7Li abundance: if there is a high density region of $\eta > 10^{-5}$ in the BBN era, amounts of produced ^7Li decreases significantly. As a consequence, the average value of ^7Li between the high and the low density regions becomes lower than the predicted value in SBBN [46].

Finally, we would like to emphasize that the nuclear reaction rates responsible to the production of He and D are still not definite. The error bars given by NACRE II [30] may not be always confirmed by other experimental groups.

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